JOURNAL OF PETROLOGY | VOLUME 52 | NUMBER 1 | PAGES 39–53 | 2011 | doi:10.1093/petrology/egq070

On Ferroan (A-type) Granitoids: their Compositional Variability and Modes of Origin

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RECEIVED APRIL 17, 2010; ACCEPTED OCTOBER 19, 2010
ADVANCE ACCESS PUBLICATION NOVEMBER 25, 2010

We recognize eight types of ferroan granitoid that can be distinguished on the basis of major element chemistry. These include alkalic granitoids that may be metaluminous or peralkaline, alkali-calcic granitoids that may be metaluminous, peraluminous or peralkaline, calc-alkalic granitoids that may be metaluminous or peraluminous, and rare calcic ferroan granitoids. These granitoids may form by two distinct end-member processes. Extreme differentiation of basaltic melts results in ferroan granitoids that are either peralkaline alkalic and alkali-calcic, or metaluminous alkalic, alkali-calcic, and calc-alkalic, with alkalinity increasing with increasing pressure of differentiation. Partial melting of tonalitic to granodioritic crust produces alkali-calcic to calc-alkalic granitoids that are metaluminous at low pressures and peraluminous at high pressures. It is likely that a combination of these two processes plays some role in the formation of most ferroan granitoids. Most granitoids that are referred to as 'A-type' are ferroan. However, the term 'A-type' has become more confusing than edifying because it has been applied to a broad spectrum of granitoid compositions with varying petrogenesis. For this reason we recommend that the term 'A-type' be discontinued and 'ferroan' used in its stead.

KEY WORDS: *A-type; classification; ferroan; granite; granitoid; petrogenesis*

INTRODUCTION

It has been more than 30 years since Loiselle & Wones (1979) defined the term 'A-type granite.' At the time, their abstract represented an important contribution to igneous petrology by identifying a previously unrecognized group of iron-enriched granitoids that occur in intra-continental environments. They defined A-type granitoids chemically as containing high Fe/(Fe + Mg), high K_2O and K_2O/Na_2O, high incompatible trace element contents (including REE, Zr, Nb and Ta), and low concentrations of trace elements compatible in mafic silicates and feldspars. Loiselle & Wones (1979) identified as type examples granitoids from the Pikes Peak batholith of Colorado, USA, the White Mountain Magma Series of New Hampshire, USA, the Nigerian Younger Granites, and the Gardar Province, Greenland (Fig. 1).

Although the definition of A-type was specific in this original abstract, referring to low H_2O and oxygen fugacity granitoids derived from an alkali basalt parental magma, the term has subsequently been applied to a much broader spectrum of granitic compositions. Collins *et al.* (1982) proposed that the Gabo and Mumbulla suites of southeastern Australia were A-type on the basis of their high $(K_2O + Na_2O)/Al_2O_3$ ratios, but defined the group mainly on trace element characteristics including high Nb, Ga, Y and REE. High Ga/Al ratios were suggested to be diagnostic of A-type granitoids, a feature that Whalen *et al.* (1987) incorporated into discrimination diagrams involving Ga/Al and Zr, Nb, Ce and Y. Using the classification of Frost *et al.* (2001), it is clear that the Australian examples of A-type granitoids are distinct from the suites that were originally used to define the term (Fig. 1). The Australian examples are ferroan, like the examples cited by Loiselle & Wones, but they are less strongly alkalic. Most of the Collins *et al.* (1982) A-type granitoids are calc-alkalic, not alkalic to alkali-calcic like those identified by Loiselle & Wones. In addition, they tend to be peraluminous, rather than metaluminous.

Eby (1990, 1992) subdivided A-type granitoids into two groups on the basis of trace element abundances, particularly the Y/Nb ratio. The group with lower Y/Nb ratios (group A1, with $Y/Nb < 1{\cdot}2$) includes felsic rocks from oceanic islands and continental rifts; these granitoids were suggested to form from an oceanic island basalt source in

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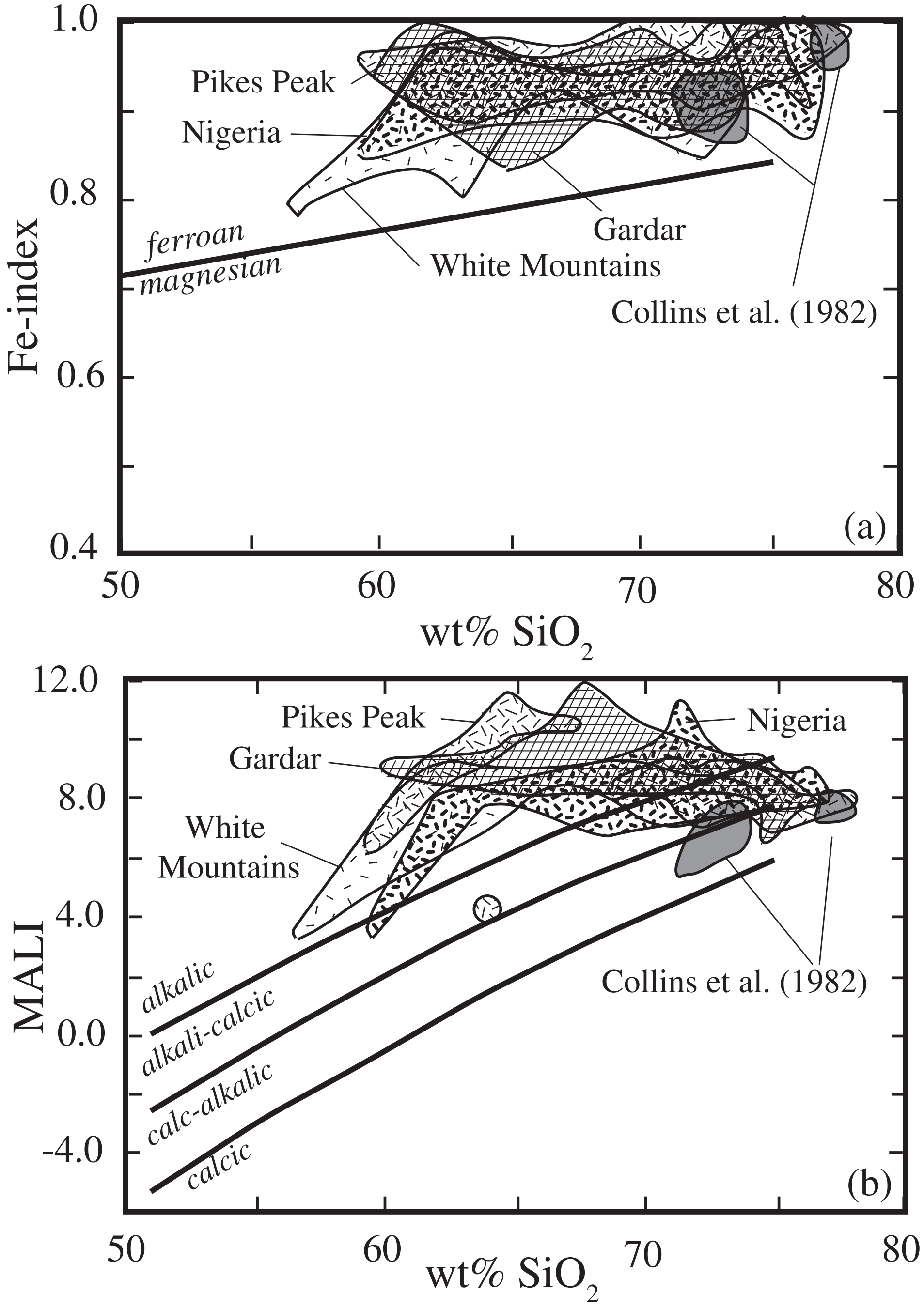

Fig. 1. Compositions of granitoids used to define A-type granites by Loiselle & Wones (1979) and Collins *et al.* (1982). (a) Fe-index = $(FeO + 0{\cdot}9Fe_2O_3)/(FeO + 0{\cdot}9Fe_2O_3 + MgO)$ vs SiO_2; boundary between ferroan and magnesian rocks from Frost & Frost (2008). (b) MALI (modified alkali lime index; $Na_2O + K_2O - CaO$) vs SiO_2; boundaries between calcic, calc-alkalic, alkali-calcic and alkalic granitoids from Frost *et al.* (2001). Data from Chapman & Williams (1935), Jacobson *et al.* (1958), Barker *et al.* (1975), Orajaka (1986), Henderson *et al.* (1989), Smith *et al.* (1999), Goodenough *et al.* (2000), Marks *et al.* (2003) and Riishuus *et al.* (2008).

an intraplate or rift setting. The group with higher Y/Nb (group A2, with Y/Nb > 1·2) was proposed to form by a number of different mechanisms: from an island arc or continental margin basalt source, or from crustal sources such as tonalite or granodiorite, or by partial melting of crust from which a melt was previously extracted (Eby, 1992). In addition, crustal contamination of A1 group granitic magmas may increase Y/Nb such that they plot in the A2 field (Eby, 1992). A1 granitoids are ferroan and metaluminous, and range from alkalic to calc-alkalic.

Of Loiselle & Wones' examples, the White Mountain and Nigerian granites belong to the A1 group, as do the sodic series of Pikes Peak granites and some Gardar granites (Eby, 1990; Smith *et al.*, 1999; Goodenough *et al.*, 2000). A2 granitoids include a greater diversity of compositions, from metaluminous to peraluminous to peralkaline, and from alkalic to calc-alkalic. The potassic series of Pikes Peak granites and some Gardar granites belong to group A2 (Smith *et al.*, 1999; Marks *et al.*, 2003).

Anderson & Bender (1989) noted that most of the A-type granitoids from the southwestern USA contain magnetite. Dall'Agnol & Oliveira (2007) called these and other similar magnetite-bearing granitoids 'oxidized A-type' granitoids. These granitoids are less strongly ferroan, mainly calc-alkalic, and commonly peraluminous. The 'oxidized A-type granites' are more magnesian than the strongly reduced A-type granitoids identified by Loiselle & Wones (1979), and hence crystallized at a higher oxygen fugacity. However, they are generally less oxidized than magnesian granitoids. This makes the term 'oxidized A-type' confusing at best.

Because the term 'A-type' has been applied to rocks with a wide variety of compositions it has become ambiguous. Here we review the variety of granitoid compositions that have been called 'A-type' and discuss their modes of origin. We conclude that, as Creaser *et al.* (1991) proposed nearly 20 years ago, the term 'A-type' be discontinued and we suggest it be replaced by the non-genetic term 'ferroan'.

PETROGENESIS OF FERROAN GRANITOIDS

Many origins have been proposed for A-type granitoids. Loiselle & Wones (1979) suggested that they form by fractionation of mantle-derived alkali basalt, with or without crustal interaction. They proposed that the crustal component may be granulite-facies lower crust that had undergone a previous partial melting episode, an idea based on the study by Barker *et al.* (1975) of the Pikes Peak batholith in which such a contaminant was hypothesized. Collins *et al.* (1982) suggested that melting of this residual felsic granulite source alone may produce A-type granitoids. They proposed that high-temperature, vapor-absent melting of such a source would generate a relatively anhydrous melt containing halides and large, high-charge cations such as Zr and REE that are abundant in A-type granitoids. However, this proposed origin is not possible for reasons presented by Creaser *et al.* (1991): previously partially melted crust will be depleted in silica and potassium, and have lower Fe/Mg than its original protolith. Partial melts from such a source should show those major element geochemical characteristics, which are opposite to those observed in A-type granitoids. Alternatively, Anderson (1983) suggested that the major element compositions of A-type granitoids may be derived by partial melting of quartz diorite, tonalite, and granodiorite. Creaser *et al.* (1991) argued that 15–40% melting of such a source could produce the appropriate water contents and geochemical characteristics of many A-type granitoids.

Thus from the earliest studies of the petrogenesis of A-type granitoids, three main modes of origin have been proposed to produce ferroan granitic compositions: (1) partial melting of quartzofeldspathic crustal rocks; (2) differentiation of basaltic magma; (3) a combination of the first two models, in which differentiating basaltic magmas assimilate crustal rocks.

Partial melting of quartzofeldspathic crust

Experimental results suggest that partial melting of calc-alkalic magnesian granitoids can produce ferroan granitoids. For example, Skjerlie & Johnston (1993) undertook dehydration melting experiments on a magnesian tonalite gneiss containing ~20% biotite and ~2% hornblende. Melts produced at 10 kbar are ferroan, as are the first melts produced at 6 kbar (Fig. 2). At 10 kbar biotite dehydration melting produces strongly ferroan melts by incongruent melting reactions that also produce orthopyroxene. With greater degrees of melting, the melt compositions approach the ferroan–magnesian boundary (Fig. 2). The first melts at 6 kbar are slightly ferroan, but cross into the magnesian field with greater degrees of melting. Importantly, these experimental melts are strongly peraluminous, especially at low degrees of melting (Fig. 2c). Patiño Douce (1997) performed dehydration melting experiments on a magnesian tonalite (~13% biotite and ~13% hornblende) and a granodiorite (~7% biotite and 6% amphibole) at 950°C at 4 and 8 kbar. Dehydration melting of both tonalite and granodiorite at 4 kbar produces Ca-rich plagioclase, orthopyroxene and minor clinopyroxene. At 8 kbar clinopyroxene is abundant, less so orthopyroxene, and plagioclase is essentially absent. These experiments showed the importance of pressure as well as source composition: the 4 kbar conditions that produce plagioclase and orthopyroxene yield melts that are ferroan and metaluminous. When little to no plagioclase and orthopyroxene crystallize and clinopyroxene is produced, as at 8 kbar, the melts are magnesian and peraluminous (Fig. 2). These experiments confirm that ferroan granites may form by dehydration melting of magnesian calc-alkalic granitoids, but only if melting takes place in the shallow crust.

A ferroan granodiorite was the starting composition for 4 kbar vapor-excess melting experiments of Bogaerts *et al.* (2006). The first melts are siliceous, strongly ferroan, and slightly peraluminous. (Fig. 2a and c). Only with high degrees of melting (>75% melt) do melt compositions decrease to less than 70% SiO_2 and trend to more

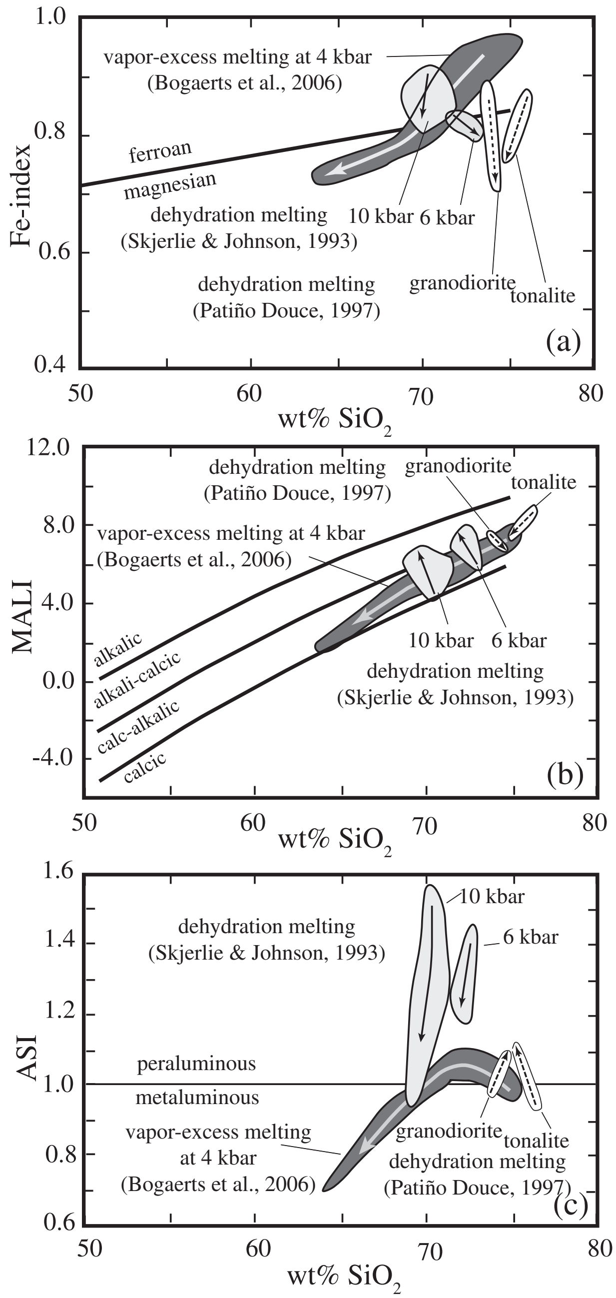

Fig. 2. Compositional trends of melts from partial melting experiments on quartzofeldspathic rocks. (a) Fe-index vs SiO_2. (b) MALI vs SiO_2, (c) ASI [aluminium saturation index; Al/(Ca −1·67P + Na + K)] vs SiO_2. Arrows show trends followed by the melt with increasing T (i.e. degree of melting) for Skjerlie & Johnston (1993) and with increased pressure (4 kbar at the tail of the arrow and 8 kbar at the arrowhead) for Patiño Douce (1997). Like the results from Patiño Douce (1997), and Skjerlie & Johnston (1993), experiments by Bogaerts *et al.* (2006) produce mainly high-silica partial melts; only with high degrees of melting (>75% melt) do melt compositions decrease to less than 70% SiO_2. Data from Skjerlie & Johnston (1993), Patiño Douce (1997) and Bogaerts *et al.* (2006).

magnesian and metaluminous compositions. All partial melts are calc-alkalic (Fig. 2b).

These experiments predict that the ferroan granitoids produced by partial melting of tonalitic to granodioritic crust will be high-silica, calc-alkalic rocks. Only with high degrees of partial melting do any of the Skjerlie & Johnston (1993) partial melts approach alkali-calcic compositions. Relatively low-pressure conditions are required to obtain metaluminous to slightly peraluminous ferroan compositions; higher pressures produce strongly peraluminous melts (Fig. 2).

Differentiation of tholeiites

Frost & Frost (1997) argued that ferroan granitoids can form as residual magmas following fractional crystallization of tholeiitic melts. The clearest evidence of this comes from tholeiitic volcanism in ocean islands that are far from continental crust, such as the Galapagos (McBirney & Williams, 1969) and Iceland (Carmichael, 1964). The rhyolites in these volcanoes could only have formed by differentiation of the basalt or melting of the basaltic wall-rock, processes that are geochemically similar.

The late-stage differentiates of tholeiites are iron-rich (Figs 3a and 4a) because tholeiitic rocks crystallize at oxygen fugacities of 1 or 2 log units below FMQ (the fayalite–magnetite–quartz buffer) (Frost & Lindsley, 1992) and consequently crystallization of magnetite is delayed (Frost & Frost, 1997). Evidence for late crystallization of magnetite during fractional crystallization of tholeiitic melts is well documented. The importance of magnetite crystallization was noted in the basalts of Thingmuli, wherein magnetite forms in the groundmass in the tholeiites and occurs as a phenocryst only in the more evolved rocks (Carmichael, 1964). In addition, magnetite did not appear as a cumulate phase in the Kiglapait intrusion until the pluton had undergone 88·6% solidification (Morse, 1980), and not until the base of the upper zone of the Bushveld intrusion (Atkins, 1969). The onset of magnetite crystallization causes the differentiation trends of the tholeiitic suites to change from iron enrichment to silica enrichment (Figs 3a and 4a), an observation that was made long ago by Osborn (1959).

The tholeiitic suites behave on a MALI (modified alkali–lime index) diagram in a similar way to their evolution on a plot of Fe-index vs silica (Figs 3a, b and Fig 4a, b). At low silica there is an increase in MALI with little change in silica, which is followed by a silica-enrichment trend that generally follows the boundaries between the alkalic, alkali-calcic, calc-alkalic, and calcic groups. As noted by Frost & Frost (2008), the boundaries between these MALI groups generally reflect the controls of feldspar crystallization. Thus as long as feldspars are crystallizing, fractional crystallization of a melt will drive it along a trend that is parallel to these boundaries. On the other hand, fractional crystallization of augite without

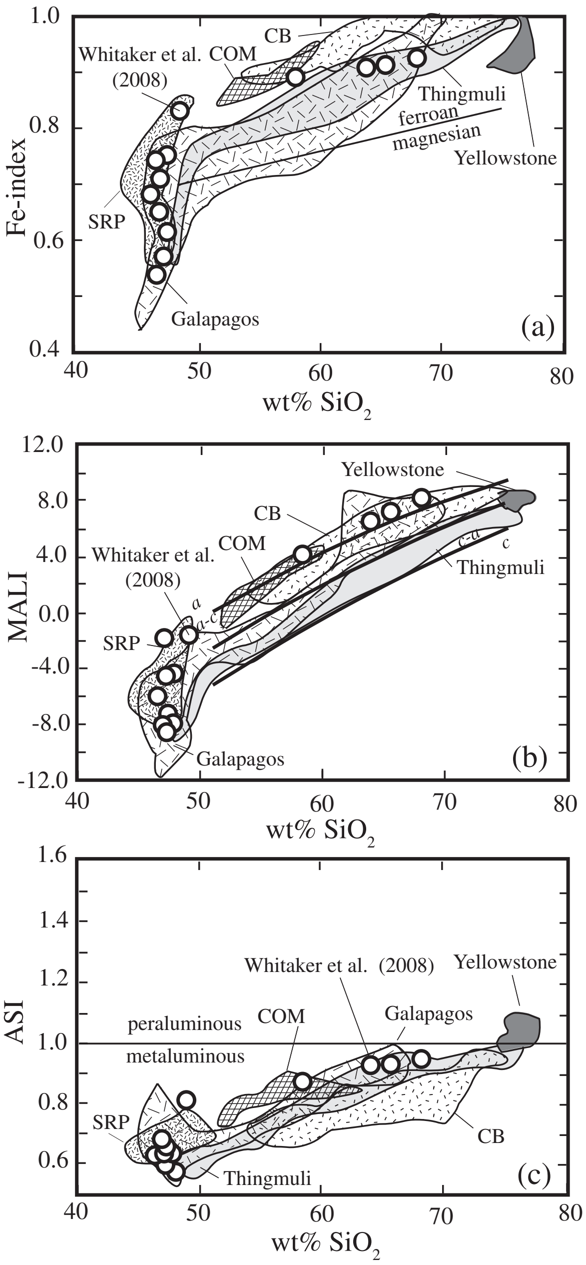

Fig. 3. (a–c) Compositional trends followed during differentiation of tholeiitic basalt. Abbreviations: a, alkalic; a-c, alkali-calcic; c-a, calc-alkalic; c, calcic. CB, Cedar Butte, Snake River Plain; COM, Craters of the Moon, Snake River Plain; SRP, Snake River Plain basalts. Data from McDougall (1962), Carmichael (1964), McBirney & Williams (1969), Baltis & Lindstrom (1980), Hildreth *et al.* (1991) and McCurry *et al.* (2008). Also shown (circles) are compositions of solids formed experimentally by crystallization of SRP tholeiites at 4·3 kbar (Whitaker *et al.*, 2008).

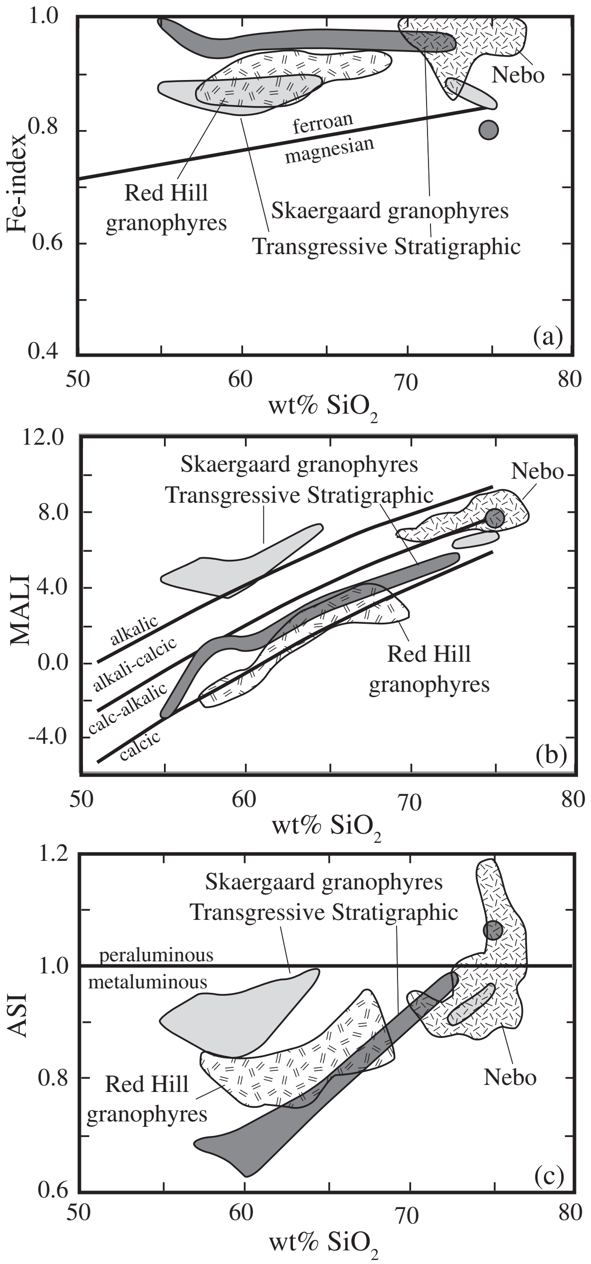

Fig. 4. Geochemical characteristics of granitic rocks associated with mafic intrusions. (a) Fe-index vs SiO_2. (b) MALI vs SiO_2, (c) ASI vs SiO_2. Data from McDougall (1962), Wager & Brown (1967), Kleeman & Twist (1989), Hirschmann (1992) and Hill *et al.* (1996).

feldspar will have the effect of driving the residual melt to higher MALI values. Thus the point at which the trend from MALI enrichment to silica enrichment occurs during the differentiation of basalt is dependent on the amount of clinopyroxene that has crystallized before plagioclase begins to crystallize. Increasing pressure tends to increase the stability of clinopyroxene relative to plagioclase until at high pressures clinopyroxene crystallizes before plagioclase (Fram & Longhi, 1992; Scoates & Lindsley, 2000; Whitaker *et al.*, 2007).

The different trends characteristic of volcanic and plutonic suites (Figs 3b and 4b) reflect the pressures at which these suites crystallized. This is evident by comparing the compositional trends of ferroan granitoids associated with differentiated mafic intrusions (Fig. 4) and the results of experimental studies on the Snake River Plain (SRP) lavas (Fig. 3) (Whitaker *et al.*, 2008). The hypabyssal Red Hill diabase, which crystallized and differentiated at shallow depths (McDougall, 1962), follows a silica-enrichment trend that lies on the calcic–calc-alkalic boundary. The Skaergaard intrusion, which crystallized at around 800 bars pressure (Lindsley *et al.*, 1969), follows a calc-alkalic trend that is slightly more alkalic than the granophyres of the Red Hill diabase. In contrast, the silica-enrichment trend followed by the evolved magmas of the Snake River Plain follows the alkali-calcic–alkalic boundary. Experimental crystallization of SRP tholeiites at 4·3 kbar duplicates this trend (Whitaker *et al.*, 2008). Presumably, differentiation of Thingmuli and Galapagos magmas took place at intermediate pressures.

The rocks formed by differentiation of basalt show an increase in aluminium saturation index (ASI) with increasing silica (Fig. 3c). However, except for the rhyolites of Yellowstone, even the most siliceous rocks remain metaluminous. Yellowstone rhyolites are slightly peraluminous but it is possible that their slightly peraluminous nature was produced by assimilation of crustal melts. The Yellowstone rhyolites have Sr and Nd isotopic compositions that suggest they have assimilated more Archean crust than the basalts (Hildreth *et al.*, 1991). In contrast, the Cedar Butte rhyolites are metaluminous and have Nd and Sr isotopic compositions suggesting they have assimilated smaller volumes of Archean crust than did the Yellowstone rhyolites (McCurry *et al.*, 2008).

Ferroan granitoids formed by differentiation in layered mafic intrusions show similar pressure relationships to the volcanic rocks (Fig. 4). Granophyres of the Red Hill diabase are mostly calc-alkalic, but a few samples are calcic. These are the only examples of ferroan calcic granitoids we have found in the literature. It is not surprising that ferroan calcic granitoids are so rare, as rocks of this composition form only as a result of very low-pressure fractionation of basalt and there are few environments that are likely to be lower pressure than the Red Hill diabase.

A wide variety of granophyres are associated with the Skaergaard intrusion. Some of them are broadly stratigraphic, others are cross-cutting and are referred to as the 'transgressive granophyres' (Wager & Brown, 1967). Some of the granophyres in the Skaergaard region contain crustal xenoliths and are clearly formed by melting of local crustal rocks; these tend to be magnesian (Geist & White, 1994). The stratigraphic granophyres reported by Wager & Brown (1967) are ferroan and calc-alkalic, and define a trend parallel to the calc-alkalic–calcic boundary. The most siliceous of these granophyres is magnesian and peraluminous and is likely to have assimilated crustal components. The so-called transgressive granophyres are distinct from the other granophyres in that they are mostly alkalic. This more alkalic composition is consistent with the conclusions of Hirschmann (1992) that the transgressive granophyres formed by differentiation and contamination of an intrusion that lay below the Skaergaard intrusion and then were intruded, cross-cutting the main intrusion.

Another example of a ferroan granitoid associated with a mafic intrusion is the Nebo granite of the Bushveld complex. It is a sheet-like body, 2–3 km thick, which was emplaced between the Layered series of the Bushveld intrusion and the overlying felsic volcanic rocks. Compositionally it is variable. In the area studied by Kleeman & Twist (1989) it is strongly ferroan and metaluminous, whereas in the areas studied by Hill *et al.* (1996), it is more magnesian and tends to be peraluminous (Fig. 4). The highly ferroan and metaluminous portions of the Nebo studied by Kleeman & Twist (1989) have the composition one would expect from differentiation of a mafic magma. The Nebo was emplaced at pressures of <1 kbar (Kleeman & Twist, 1989) to 2 kbar (Pitra & De Waal, 2001); it was probably generated by differentiation at a higher pressure. If the pressure dependence of MALI in ferroan granitoids is valid, then the pressure at which the Nebo differentiated is likely to have been less than the 4·3 kbar used in the experiments of Whitaker *et al.* (2008) (Fig. 3).

Some parts of the Nebo granite have clearly assimilated continental crust. This is indicated by the peraluminous nature of many of the Nebo samples analysed by Hill *et al.* (1996). In addition, many samples have unradiogenic initial Nd isotopic compositions and there is a positive correlation between oxygen isotopic compositions and ASI, such that the more contaminated samples are higher in both (Hill *et al.*, 1996).

Combined crustal assimilation–fractional crystallization models for the origin of ferroan granitoids

From the above discussion it is clear that ferroan granitoids can form either by low-pressure partial melting of magnesian quartzofeldspathic rocks or by differentiation of tholeiitic basalt. Evidence for these end-member processes is provided by partial melting and crystallization experiments. However, natural ferroan suites demonstrate that these processes commonly are coupled. For example, both the Yellowstone rhyolites (Fig. 3) and the Nebo granite, which are associated with extensively differentiated basaltic rocks, show evidence of crustal assimilation (Hildreth *et al.*, 1991; Hill *et al.*, 1996). Ferroan granitoids are commonly associated with basaltic rocks (Rämö & Haapala, 1995; Frost *et al.*, 1999). Moreover, the magmatic temperature of ferroan granitoids is high, >900°C (see Creaser *et al.*, 1991; Patiño Douce, 1997). These two observations suggest that to attain these high liquidus temperatures requires the participation of hot mafic magmas. These magmas may provide only the heat necessary for crustal melting or they may contribute mass through differentiation and assimilation of crustal melts. Ferroan granitoids are generally interpreted to form in extensional tectonic regimes, in which the crust is thin and mantle heat and basaltic magma can approach the Earth's surface (Anderson, 1983; Haapala & Rämö, 1990). In this environment it is expected that differentiating basaltic magmas may be contaminated to some degree by the quartzofeldspathic wall-rocks through which they ascend.

VARIETIES OF FERROAN GRANITOIDS

Frost *et al*. (2001) and Frost & Frost (2008) showed that indices based upon major elements are surprisingly powerful in distinguishing groups of granitic rocks. Indeed, major element compositions may be the most appropriate basis for granitoid classification, because unlike in basalts, trace elements in granitic rocks commonly are not incompatible (Bea, 1996). Elements such as REE, U, Th, and Zr reside in minor mineral phases such as apatite, zircon, titanite, allanite and monazite. Other trace elements, including Nb and Y, are concentrated in oxides and amphiboles, among other minerals, and their abundances may reflect the crystallization history and intensive parameters (oxygen and water fugacity) as much as the composition of the parental magma. Crustal contamination also commonly has a much larger influence on the trace element abundances in a granitic melt than on its major element composition. Thus, reliance on trace element abundances and ratios as discriminators in granitoid rocks may not unambiguously identify magma source or tectonic setting.

Discrimination based upon five indices, including Fe* (ferroan vs magnesian), MALI, ASI, AI (alkalinity index), and FSSI (feldspathoid silica saturation index) (Frost *et al.*, 2001; Frost & Frost, 2008) allows us to recognize eight groups of ferroan granitoid (Table 1).

Alkalic metaluminous granitoids

Many alkalic, metaluminous ferroan granitoids are associated with massif anorthosites and layered mafic intrusions and may be referred to as rapakivi granites because rapakivi texture is a common feature (Rämö & Haapala, 1995). The rocks associated with this group of granitoids cover a wide range of silica contents (Fig. 5). The most silica-poor portions of this suite are ferrodiorite and monzodiorite (also called jotunite). These grade into monzonites and syenites, which at higher silica contents may contain minor amounts of free quartz. True granites, some of which may be alkali-calcic, occupy only a small proportion of the rock types in these suites (Fig. 5).

Alkalic metaluminous ferroan granitoids are metaluminous, presumably because assimilation of aluminous crust to make them peraluminous would also drive the granitoid compositions towards calc-alkalic. In fact, assimilation of felsic crust may be responsible for the trend from alkalic to alkali-calcic compositions for some granitic bodies at high silica: the highest silica members of the Sybille and Red Mountain intrusions exhibit Nd and Sr isotopic compositions indicative of assimilation of felsic Archean crust (Scoates *et al.*, 1996; Anderson *et al.*, 2003).

The ferroan alkalic granitoids (Fig. 6) have been interpreted as forming by fractional crystallization of a ferrobasalt parent magma at moderately high pressure and with minor crustal contamination (Duchesne & Wilmart, 1997; Frost *et al.*, 1999), which is consistent with their

Table 1: The eight groups of ferroan granitoids

Type	Example	Reference
Alkalic metaluminous	Bjerkreim–Sokndal, Norway	Duchesne & Wilmart (1997)
Alkalic peralkaline	Lireui, Nigeria	Jacobsen *et al*. (1958); Orajaka (1986)
Alkali-calcic metaluminous	Sherman granite, Wyoming, USA	Frost *et al*. (1999)
Alkali-calcic peraluminous	Lincoln granite, Wyoming, USA	Frost *et al*. (1999)
Alkali-calcic peralkaline	Brandberg, Namibia	Schmitt *et al*. (2000)
Calc-alkalic metaluminous	Granophyres of Skaergaard, Greenland	Wager & Brown (1967)
Calc-alkalic peraluminous	Mumbulla suite, Australia	Collins *et al*. (1982)
	Carajás, Brazil	Dall-Agnol & Oliveira (2007)
Calcic metaluminous	Red Hill granophyres, Australia	McDougall (1962)

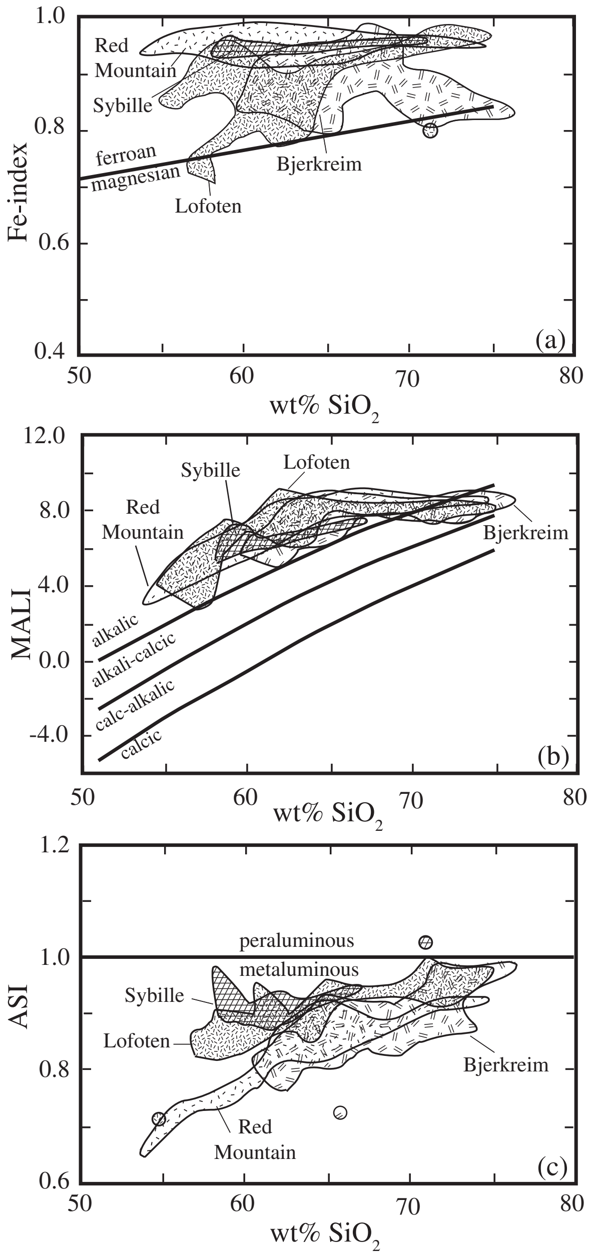

Fig. 5. Compositional trends of ferroan alkalic granitoids. (a) Fe-index vs SiO$_2$. (b) MALI vs SiO$_2$, (c) ASI vs SiO$_2$. Data from Malm & Ormaasen (1978), Scoates *et al.* (1996), Duchesne & Wilmart (1997) and Anderson *et al.* (2003).

geochemical similarities to the higher pressure volcanic suites such as the lavas of the Snake River Plain (see Fig. 3).

Alkalic and alkali-calcic peralkaline granitoids

Peralkaline granitoids tend to be strongly ferroan and may be either alkalic or alkali-calcic (Fig. 7). Some suites, such as Puklen, Kiuqi, and the Saudia Arabian granitoids, have both alkalic and alkali-calcic components. In addition, some batholiths containing peralkaline granitoids, such as Puklen and Brandberg, also include monzonitic and syenitic components and hence have silica contents as low as 60%. Most plutons containing peralkaline granitoids also have components that are either metaluminous or peraluminous (Fig. 6a). Some of the Saudi Arabian granitoids, for example, are concentrically zoned and single plutons may contain metaluminous, peraluminous, and peralkaline components. The calc-alkalic Saudi Arabian granitoid samples are peraluminous, not peralkaline (Stuckless *et al.*, 1982; Stoeser & Frost, 2006).

It is likely that peralkaline granitoids form largely by differentiation of transitional or alkali basalt because peralkaline volcanic suites, such as Boina, Nyambeni, and Suswa (Nash *et al.*, 1969; Barberi *et al.*, 1975; Brotzu *et al.*, 1983) have been shown to have formed by fractional crystallization of a transitional basalt (Frost & Frost, 2008). This is a manifestation of the plagioclase effect (Bowen, 1945), whereby crystallization of Ca-rich plagioclase extracts Al over Na in the melt, decreasing the alkalinity index of the magma and producing peralkaline compositions.

It is likely that the peraluminous portions of the plutons that contain peralkaline granitoids are the products of crustal melting. A model for how this may happen is shown in Fig. 6b, which is a plot of AI vs FSSI. In light gray on this diagram we show the differentiation trends for Boina, which produced peralkaline rhyolites by differentiation of transitional basalts, and for Nyambeni, which produced peralkaline phonolites by differentiation of alkali basalt (Frost & Frost, 2008). Also shown in gray is a field for the compositions of ferroan granitoids produced by experimental melting of granitic rocks (Skjerlie & Johnston, 1993; Patiño Douce, 1997; Bogaerts *et al.*, 2006). It is obvious that the compositions of the granitic bodies that contain peralkaline units bridge the trends between Boina and the experimentally derived melts. The only suite that is not bounded by the Boina trend is Puklen, which extends to more peralkaline compositions. Puklen differs from the rest of the peralkaline granitoids in that it apparently formed by contamination of a nepheline syenite (Marks *et al.*, 2003), which is consistent with the fact that it is bounded at low FSSI by the Nyambeni trend (Fig. 6b).

The data shown in Fig. 6 suggest that, apart from a few examples that form by crustal contamination of alkali syenites, most peralkaline ferroan granitoids form by differentiation of transitional basalts (Boina trend). Contamination of these peralkaline differentiates with crustal melts similar to those produced by partial melting experiments produces granitoids that trend to metaluminous compositions (Liruei, Brandenburg, Kuiqi, and Saudi Arabian granites).

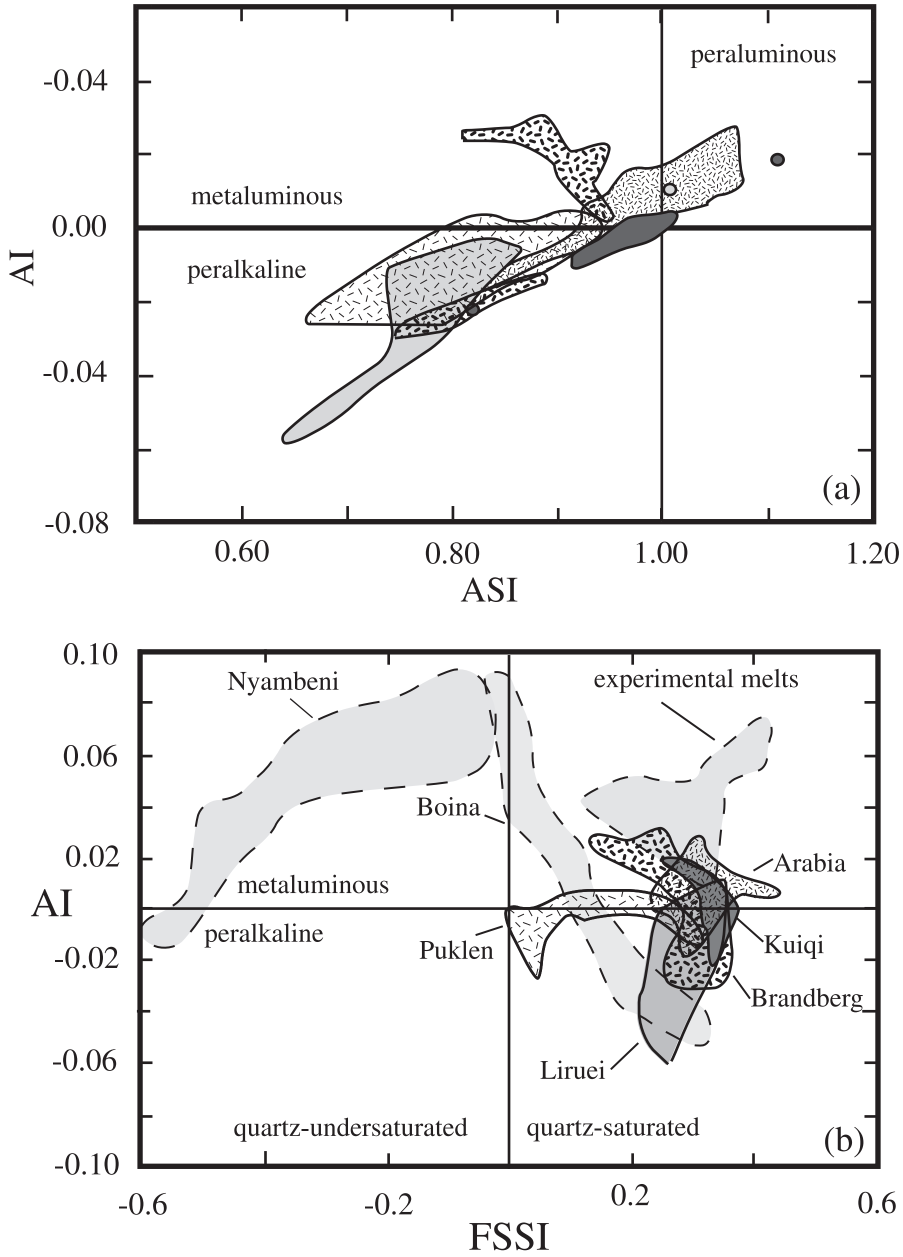

Fig. 6. Compositional variability in plutons that contain peralkaline granitoids. (a) AI [alkalinity index; Al – (K + Na)] vs ASI, (b) AI vs FSSI (feldspathoid silica-saturation index; normative [Q – Lc – 2(Ne + Kp)]/100) (Frost & Frost, 2008) comparing the differentiation trends of peralkaline granitoids (sources of data as in Fig. 7) with those of volcanic rocks at Boina (Barberi *et al.*, 1975) and Nyambeni (Brotzu *et al.*, 1983), and experimental melts of granitic rocks (Patiño Douce, 1997).

Alkali-calcic metaluminous and peraluminous granitoids

As with the alkalic suites, alkali-calcic batholiths display a range of silica contents (Fig. 8). Examples of alkali-calcic ferroan granitoids include the Mesoproterozoic San Isabel and Sherman batholiths of the southwestern USA (Cullers *et al.*, 1992; Frost *et al.*, 1999) and the Suomenniemi batholith of the Finnish rapakavi granite association (Rämö, 1991; Fig. 8). The Sherman and San Isabel batholiths do have a monzonitic component (Frost *et al.*, 1999), but most of the silica variation in the Sherman and the San Isabel is caused by a large variation in the abundance of ferromagnesian minerals in the granitoids themselves. Cullers *et al.* (1992) and Frost *et al.* (1999) argued that some of this variation is caused by incomplete mixing of basaltic magma with granitic magma. Unlike the alkalic ferroan

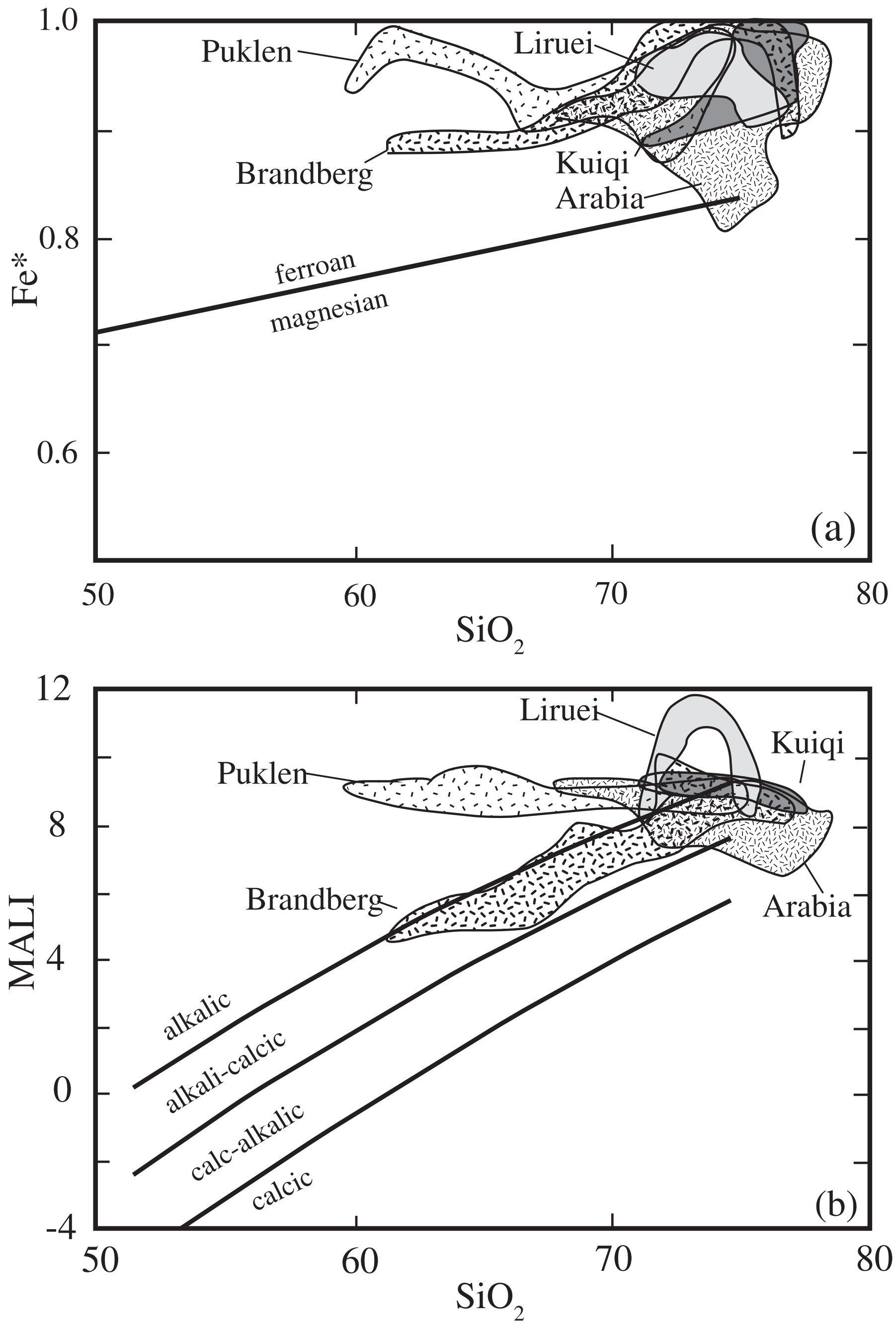

Fig. 7. Compositional trends of ferroan peralkaline granitoids. (a) Fe* vs SiO$_2$. (b) MALI vs SiO$_2$. Data from Stuckless *et al*. (1982), Orajaka (1986), Martin *et al*. (1994), Schmitt *et al*. (2000) and Marks *et al*. (2003).

granitoids, some of the alkali-calcic ferroan granitoids have peraluminous components (Fig. 8c). These peraluminous alkali-calcic granitoids appear to have assimilated a greater amount of felsic crust than metaluminous alkali granitoids. For example, in the Laramie Mountains of southeastern Wyoming, the alkalic Red Mountain and Sybille plutons were intruded into refractory Archean crust and only the most siliceous rocks assimilated more than 10–15% crust (Scoates *et al.*, 1996; Anderson *et al.*, 2003); in contrast, the alkali-calcic Sherman batholith intruded Proterozoic crust and assimilated a greater amount (Frost *et al.*, 1999, 2002). Metaluminous alkali-calcic ferroan granitoids commonly are associated with high-silica, peraluminous granites. In the Sherman batholith, the

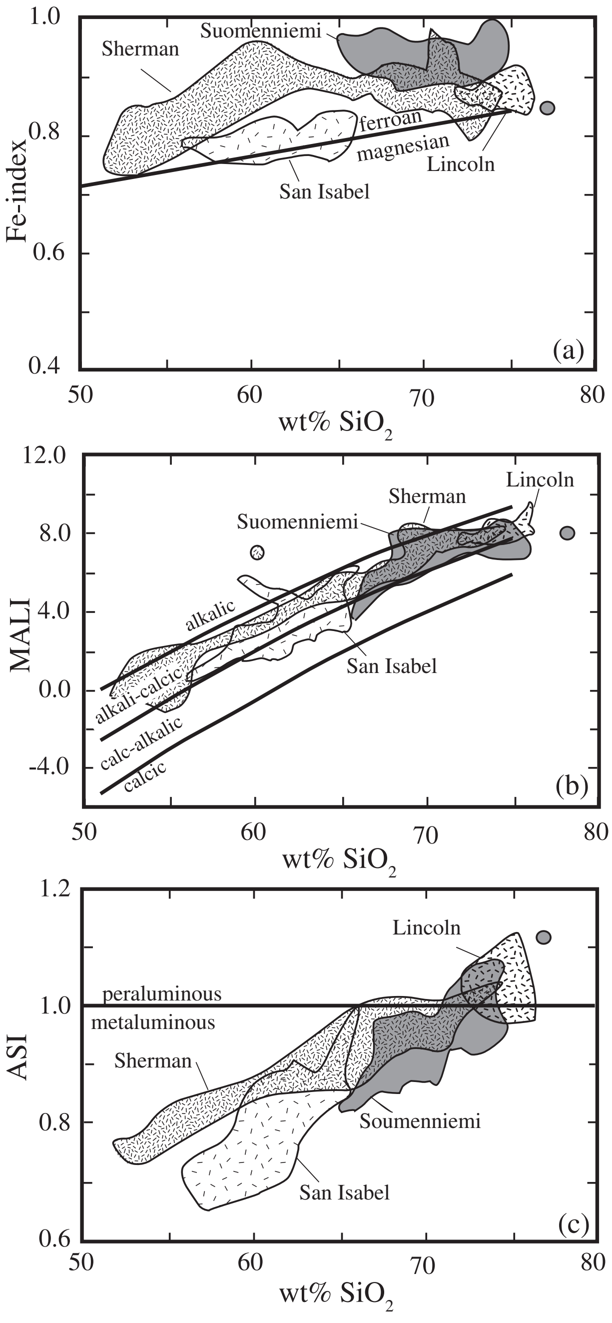

Fig. 8. Compositional trends of ferroan alkali-calcic granitoids. (a) Fe-index vs SiO_2. (b) MALI vs SiO_2, (c) ASI vs SiO_2. Data from Rämö (1991), Cullers *et al.* (1992) and Frost *et al.* (1999).

metaluminous alkali-calcic Sherman granite is intruded by fine-grained, more siliceous, peraluminous Lincoln granite. The Lincoln granite has more radiogenic initial $^{87}Sr/^{86}Sr$ and more negative initial ε_{Nd}, indicating that it assimilated a greater proportion of older continental crust than did the Sherman granite. This is consistent with its higher silica content and more strongly peraluminous nature (Frost *et al.*, 1999).

Calc-alkalic metaluminous and peraluminous granitoids

Unlike the other groups of ferroan granitoids, batholiths containing the calc-alkalic ferroan granitoids tend to lack low-silica members. Most calc-alkalic ferroan granitoids have high silica contents (>70% SiO_2; Fig. 9). They span the metaluminous–peraluminous boundary (Fig. 5c). Examples include granites from Carajas, Brazil (Dall-Agnol & Oliveira, 2007; Oliveira *et al.* 2009), which were interpreted to form by melting of quartzofeldspathic crust under relatively oxidizing conditions. Other examples from Australia have been attributed to partial melting of felsic granulite (Collins *et al.*, 1982; King *et al.*, 2001). These ferroan, calc-alkalic granitoids have compositions similar to the partial melts made experimentally (compare Figs. 9 and 2). For example, the Carajas granite was attributed by Dall'Agnol & Oliveira (2007) to partial melting of quartzofeldspathic igneous sources. An origin by partial melting also may explain the scarcity of intermediate and mafic members of the ferroan calc-alkalic granitoid suites shown in Fig. 9.

Calc-alkalic metaluminous granitoids may also form through low-pressure differentiation of tholeiitic magmas, as in the granophyres associated with the Skaergaard intrusion (Fig. 4). These granitoids are distinct from the metaluminous calc-alkalic granitoids produced by crustal melting in that they are likely to have extremely high Fe*, are clearly associated with mafic intrusions and are part of a suite of rocks that extends down to low silica contents.

Uncommon compositions of ferroan granitoids

The other compositional varieties of ferroan granitoids are either exceedingly uncommon or unknown. As we noted above, metaluminous calcic granitoids are uncommon. Only the Red Hill dolerites contain granitoids that overlap from the calc-alkalic into the calcic field (Fig. 4). As discussed above, these calc-alkalic to calcic metaluminous granitoids form as the result of low-pressure fractionation of basalt. Although theoretically possible, we have not identified any examples of ferroan alkalic peraluminous or ferroan calcic peraluminous granitoids. We suggest that ferroan calcic and calc-alkalic peralkaline granitoids should not exist, as the increase in alkalis necessary to make a rock peralkaline would also make them alkali-calcic or alkalic.

Summary

We have identified eight geochemically distinct groups of ferroan granitoid and determined that these can form by a variety of processes (Fig. 10). Differentiation of tholeiitic

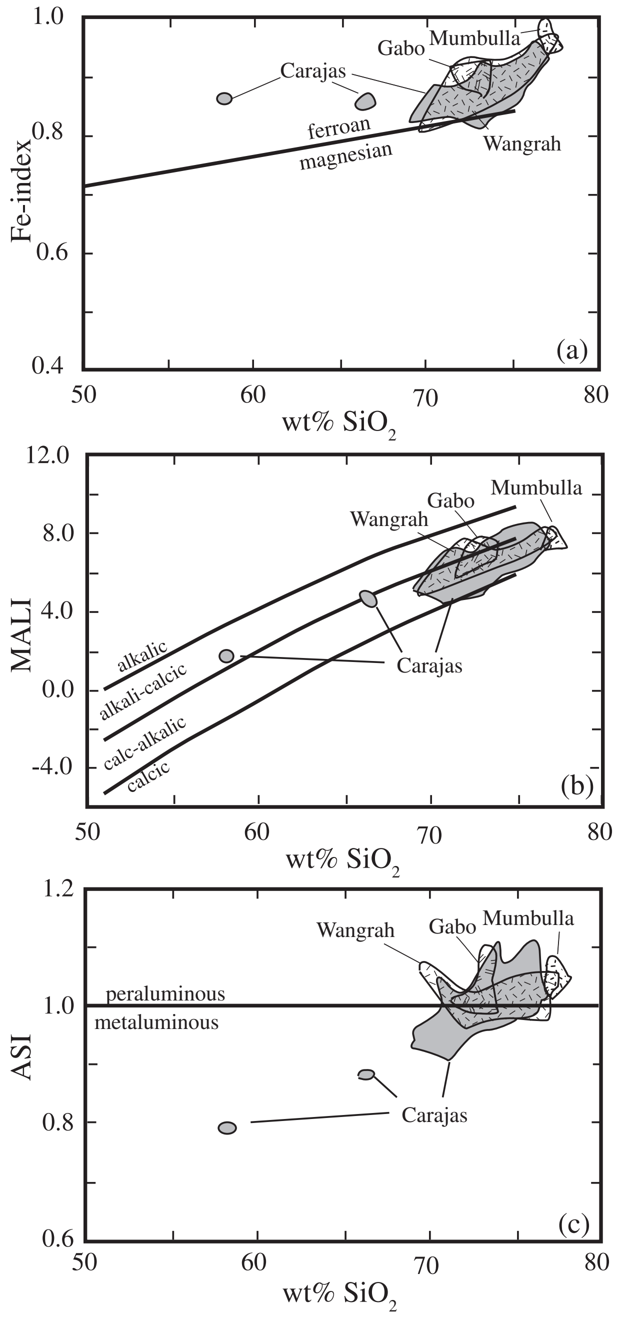

Fig. 9. Compositional trends of ferroan calc-alkalic granitoids. (a) Fe-index vs SiO_2. (b) MALI vs SiO_2, (c) ASI vs SiO_2. Data from Collins *et al.* (1982), Dall'Agnol *et al.* (1999), King *et al.* (2001), Dall'Agnol & Oliveira (2007) and Oliveria *et al.* (2009).

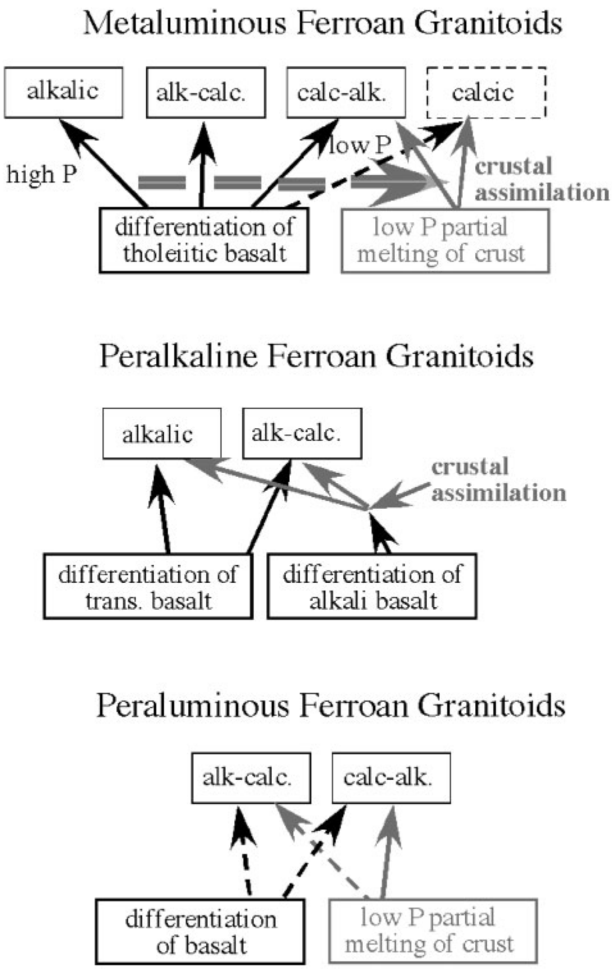

Fig. 10. Schematic illustration summarizing the petrogenesis of the different groups of ferroan granitoids. Metaluminous ferroan granitoids may form by differentiation of tholeiitic basalt. Partial melting of quartzofeldspathic crust at low pressure may form calc-alkalic metaluminous ferroan granitoids. Peralkaline ferroan granitoids form by differentiation of transitional or alkali basalt, and may be accompanied by some crustal assimilation. Ferroan granitoids become peraluminous by involvement of partial melts of granitic crust.

basalt will produce metaluminous ferroan granitoids ranging in composition from alkalic to calcic, depending upon the pressure of differentiation. In addition, low-pressure melting of quartzofeldspathic rocks may produce metaluminous calc-alkalic granitoids. Peralkaline ferroan granitoids may form by differentiation of transitional basalt or alkali basalt. Crustal contamination of peralkaline granitoids may yield metaluminous and peraluminous members of these intrusions. Peraluminous ferroan granitoids are formed by partial melting of quartzo-feldspathic crust, with or without a basaltic component (Fig. 10).

CONCLUSION: REPLACE 'A-TYPE' WITH 'FERROAN'

In present usage, the term 'A-type' is essentially synonymous with 'ferroan' as defined by Frost *et al.* (2001). We suggest that 'ferroan' replace the use of the term 'A-type' for the following reasons.

(1) Ferroan granitic rocks are those with FeO/(FeO + MgO) higher than in Cordilleran, subduction-related granitoids, and are correspondingly more reduced (Frost *et al.*, 2001). This major element geochemical index is non-genetic; that is, it does not connote a particular petrogenesis. In contrast, the term 'A-type granite' as originally defined implied descent from an alkali basalt parent. As summarized above, subsequently the term has acquired a much broader definition. Many of the rocks referred to as 'A-type' are formed by differentiation of tholeiitic, not alkali, basalt or possibly by partial melting of crustal rocks with little or no involvement of basalt. We concur with the recent review by Bonin (2007), which pointed out that the term has has been applied so indiscriminately that 'A-' may represent anorogenic, alkaline, anhydrous, aluminous, or even ambiguous.

(2) An extensional or 'anorogenic' (intraplate) environment is commonly invoked as the tectonic setting for A-type granitoids and in fact many researchers refer to A-type granitoids as 'anorogenic'. However, this setting does not yield granitic magmas of a single composition. The same composition source rock may melt in a variety of tectonic settings. For example, the intraplate rhyolites of Yellowstone are strongly ferroan and alkalic, whereas the rhyolitic Bishop tuff is calc-alkalic (Hildreth, 1979; Hildreth *et al.*, 1991). Furthermore, granitoids in extensional environments need not be ferroan: the Variscan basement of the Central Iberian Zone contains magnesian, calc-alkaline, peraluminous metagranites that have been interpreted to form during rifting and intrusion of mantle-derived mafic magmas at the base of the crust. Rapid partial melting resulted in felsic magmas that inherited the geochemical compositions of their granitic protoliths, magma compositions not typical of rift-related, extensional settings (Bea *et al.*, 2007). Therefore extension does not necessarily produce iron-enriched, potassic 'A-type' magma compositions.

(3) Use of 'A-type' is confusing. Although relating granitoid 'types' (be it A, S, I, M, etc.) to the composition of the source rock is conceptually simple, it is of little practical use. This is because similar magma compositions can be made by partial melting or differentiation of a variety of sources. Furthermore, the source rock is only one control on granitoid magma composition. Intensive parameters and processes including assimilation, magma mixing, differentiation, and fluid interaction are also very important.

Furthermore, as noted above, ferroan granitoids include a variety of compositions that can form by several distinct petrological processes. Referring to all as 'A-type' overlooks the variety of processes by which ferroan granitoids may form. This produces unnecessary confusion when these rocks of different compositions, and different likely modes of origins, are compared as the same 'type'. It leads researchers to infer controversy over the origin of A-type granitoids when in reality there is none. We have shown that ferroan alkali and alkali-calcic granitoids are likely to have evolved from basaltic melts, whereas ferroan calc-alkalic granitoids are more likely to have formed from crustal melting or to have incorporated large amounts of crustal melt. The 'controversy' arises because these various types of granitoids are lumped into a single category. It does not make sense to consider them all the same type of granitoid when they have clearly distinct chemical compositions that can have different origins.

In addition to producing an oversimplification that is crippling to our understanding of these ferroan granitoids, the term 'A-type' also handicaps the studies of single batholiths. Ferroan granitic batholiths may contain rocks of more than one composition type; for example, the Pikes Peak batholith contains both metaluminous and peralkaline granitoids (Barker *et al.*, 1975) and the Sherman batholith contains both metaluminous and peraluminous granitoids (Frost *et al.*, 1999). These different types of ferroan granitoid reflect differences in the petrogenetic processes by which the various types of ferroan granitic rocks in the batholith were formed, and to group them together is to risk overlooking the significance of their geochemical variety.

At the time it was introduced (Loiselle & Wones, 1979) the concept of A-type granitoids was a major step forward in granite petrology. However, in the 30 years since its introduction the term has become applied too broadly for modern petrology and it is time to retire the term 'A-type' in favor of 'ferroan'.

ACKNOWLEDGEMENTS

The authors thank J. Lawford Anderson, Michael McCurry, and two anonymous reviewers for their thoughtful comments. This paper is a contribution of IGCP-510, 'A-type granites and related rocks through time'.

FUNDING

This work was supported by the National Science Foundation (grant number EAR-0537670 to B.R.F., C.D.F. and S. M. Swapp).

REFERENCES

Anderson, I. C., Frost, C. D. & Frost, B. R. (2003). Petrogenesis of the Red Mountain pluton, Laramie anorthosite complex, Wyoming: implications for the origin of A-type granites. In: Medaris, L. G. Jr, Byers, C. W., Mickelson, D. M. & Shanks, W. C. (eds). *Proterozoic geology: selected papers from an international symposium, Precambrian Research* **124**, 243–267.

Anderson, J. L. (1983). Proterozoic anorogenic granite plutonism of North America. *Geological Society of America, Memoirs* **161**, 133–154.

Anderson, J. L. & Bender, E. E. (1989). Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America. *Lithos* **23**, 19–52.

Atkins, F. B. (1969). Pyroxenes of the Bushveld Intrusion, South Africa. *Journal of Petrology* **10**, 222–249.

Baltis, H. W. & Lindstrom, M. M. (1980). Geology, petrography, and petrology of Pinzon Island, Galapagos Archipelago. *Contributions to Mineralogy and Petrology* **72**, 367–386.

Barberi, F., Ferrara, G., Santacroce, R., Treuil, M. & Varet, J. (1975). A transitional basalt–pantellerite sequence of fractional crystallization, the Boina centre (Afar Rift, Ethiopia). *Journal of Petrology* **16**, 22–56.

Barker, F., Wones, D. R., Sharp, W. N. & Desborough, G. A. (1975). The Pikes Peak Batholith, Colorado Front Range, and a model for the origin of the gabbro–anorthosite–syenite–potassic granite suite. *Precambrian Research* **2**, 97–160.

Bea, F. (1996). Residence of REE, Y, TH, and U in granites and crustal protoliths, implications for the chemistry of crustal melts. *Journal of Petrology* **37**, 521–552.

Bea, F., Montero, P., Gonzalez-Lodeiro, F. & Talavera, C. (2007). Zircon inheritance reveals exceptionally fast crustal magma generation processes in central Iberia during the Cambro-Ordovician. *Journal of Petrology* **48**, 2327–2339.

Bogaerts, M., Scaillet, B. & Vander Auwera, J. (2006). Phase equilibria of the Lyngdal granodiorite (Norway): Implications for the origin of metaluminous ferroan granitoids. *Journal of Petrology* **47**, 2405–2431.

Bonin, B. (2007). A-type granites and related rocks; evolution of a concept, problems and prospects. *Lithos* **97**, 1–29.

Bowen, N. L. (1945). Phase equilibria bearing on the origin and differentiation of alkaline rocks. *American Journal of Science* **243-A**, 75–89.

Brotzu, P., Morbidelli, L. & Piccirillo, E. M. (1983). The basanite to peralkaline phonolite suite of the Plio-Quaternary Nyambeni multicenter volcanic range (East Kenya Plateau). *Neues Jahrbuch für Mineralogy, Abhandlungen* **147**, 253–280.

Carmichael, I. S. E. (1964). The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. *Journal of Petrology* **5**, 435–460.

Chapman, R. W. & Williams, C. R. (1935). Evolution of the White Mountain magma series. *American Mineralogist* **20**, 502–530.

Collins, W. J., Beams, D., White, J. R. & Chappell, B. W. (1982). Nature and origin of A-type granites with particular reference to south-eastern Australia. *Contributions to Mineralogy and Petrology* **80**, 189–200.

Creaser, R. A., Price, R. C. & Wormald, R. J. (1991). A-type granites revisited: assessment of a residual-source model. *Geology* **19**, 163–166.

Cullers, R. L., Griffin, T., Bickford, M. E. & Anderson, J. L. (1992). Origin and chemical evolution of the 1360 Ma San Isabel batholith, Wet Mountains, Colorado; a mid-crustal granite of anorogenic affinities. *Geological Society of America Bulletin* **104**, 316–328.

Dall'Agnol, R. & Oliveira, D. C. (2007). Oxidized, magnetite-series, rapakivi-type granites of Carajás, Brazil: Implications for classification and petrogenesis of A-type granites. *Lithos* **93**, 215–233.

Dall'Agnol, R., Rämö, O. T., Magalhães, M.S. & Macambira, M. J. B. (1999). Petrology of the anorogenic, oxidised Jamon and Musa granites, Amazonian Craton: implications for the genesis of Proterozoic A-type granites. *Lithos* **46**, 431–462.

Duchesne, J.-C. & Wilmart, E. (1997). Igneous charnockites and related rocks from the Bjerkreim–Sokndal layered intrusion (southwest Norway): a jotunite (hypersthene monzodiorite)-derived A-type granitoid suite. *Journal of Petrology* **38**, 281–303.

Eby, G. N. (1990). The A-type granitoids: A review of their occurrence and chemical characteristics and speculations on their petrogenesis. *Lithos* **26**, 115–134.

Eby, G. N. (1992). Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. *Geology* **20**, 641–644.

Fram, M. S. & Longhi, J. (1992). Phase equilibria of dikes associated with Proterozoic anorthosite complexes. *American Mineralogist* **77**, 605–616.

Frost, B. R. & Frost, C.D. (2008). A geochemical classification for feldspathic igneous rocks. *Journal of Petrology* **49**, 1955–1969.

Frost, B. R. & Lindsley, D. H. (1992). Equilibria among Fe–Ti oxides, pyroxenes, olive, and quartz: Part II. Application. *American Mineralogist* **77**, 1004–1020.

Frost, B. R., Arculus, R. J., Barnes, C. G., Collins, W. J., Ellis, D. J. & Frost, C. D. (2001). A geochemical classification of granitic rocks. *Journal of Petrology* **42**, 2033–2048.

Frost, C. D. & Frost, B. R. (1997). Reduced rapakivi-type granites: the tholeiite connection. *Geology* **25**, 647–650.

Frost, C. D., Frost, B. R., Chamberlain, K. R. & Edwards, B. R. (1999). Petrogenesis of the 1·43 Ga Sherman batholith, SE Wyoming: a reduced rapakivi-type anorogenic granite. *Journal of Petrology* **40**, 1771–1802.

Frost, C. D., Frost, B. R., Bell, J. M. & Chamberlain, K. R. (2002). The relationship between A-type granites and residual magmas from anorthosite: evidence from the northern Sherman batholith, Laramie Mountains, Wyoming, USA. *Precambrian Research* **119**, 45–71.

Geist, D. & White, C. (1994). Assimilation and fractionation in adjacent parts of the same magma chamber: Vandfaldsdalen macrodike, East Greenland. *Contributions to Mineralogy and Petrology* **116**, 92–107.

Goodenough, K. M., Upton, B. G. J. & Ellam, R. M. (2000). Geochemical evolution of the Ivgtut granite, South Greenland: a fluorine-rich 'A-type' intrusion. *Lithos* **51**, 205–221.

Haapala, I. & Rämö, O. T. (1990). Petrogenesis of the Proterozoic rapakivi granites of Finland. In: Stein, H. J. & Hannah, J. L. (eds) Ore-bearing granite systems; petrogenesis and mineralizing processes. *Geological Society of America, Special Papers* **246**, 275–286.

Henderson, C. M. B., Pendlebury, K. & Foland, K. A. (1989). Mineralogy and petrology of the Red Hill alkaline igneous complex, New Hampshire, U.S.A. *Journal of Petrology* **30**, 627–666.

Hildreth, W. (1979). The Bishop Tuff; evidence for the origin of compositional zonation in silicic magma chambers. In: Chapin, C. E. & Elston, W. E. (eds) Ash-flow tuffs. *Geological Society of America, Special Papers* **180**, 43–75.

Hildreth, W., Halliday, A. N. & Christiansen, R. L. (1991). Isotopic and chemical evidence concerning the genesis and contamination of basaltic and rhyolitic magma beneath the Yellowstone plateau volcanic field. *Journal of Petrology* **32**, 63–138.

Hill, M., Barker, F., Hunter, D. & Knight, R. (1996). Geochemical characteristics and origin of the Lebowa Granite Suite, Bushveld Complex. *International Geology Review* **38**, 195–227.

Hirschmann, M. (1992). Origin of the Transgressive granophyres from the Layered series of the Skaergaard intrusions, East Greenland. *Journal of Volcanology and Geothermal Research* **52**, 185–207.

Jacobson, R. R. E., MacLeod, W. N. & Black, R. (1958). Ring-complexes in the Younger Granite Province of Northern Nigeria. *Geological Society, London, Memoirs* **1**, 71 p.

King, P. L., Chappell, B. W., Allen, C. M. & White, A. J. R. (2001). Are A-type granites the high-temperature felsic granites? Evidence from fractionated granites of the Wangrah suite. *Australian Journal of Earth Sciences* **48**, 501–514.

Kleeman, G. J. & Twist, D. (1989). The compositionally zoned sheet-like granite pluton of the Bushveld Complex: Evidence bearing on the nature of A-type magmatism. *Journal of Petrology* **30**, 1383–1414.

Lindsley, D. H., Brown, G. M. & Muir, I. D. (1969). Conditions of the ferrowollastoinite–ferrohedenbergite inversion in the Skaergaard intrusion, East Greenland. In: Papike, J. J., Boyd, F. R., Clark, J. R. & Ernst, W. G. (eds) Pyroxenes and amphiboles: crystal chemistry and phase petrology. *Mineralogical Society of America, Special Papers* **2**, 193–201.

Loiselle, M. C. & Wones, D. (1979). Characteristics and origin of anorogenic granites. *Geological Society of America, Abstracts with Programs* **11**, 468.

Malm, O. A. & Ormaasen, D. E. (1978). Mangerite–charnockite intrusives in the Lofoten–Vesterålen area, North Norway: petrography, chemistry, and petrology. *Norges Geologiske Undersökelse* **338**, 83–114.

Marks, M., Vennemann, T., Siebel, W. & Markl, G. (2003). Quantification of magmatic and hydrothermal processes in a peralkaline syenite–alkali granite complex based on textures, phase equilibria, and stable and radiogenic isotopes. *Journal of Petrology* **44**, 1247–1280.

Martin, H., Bonin, B., Capdevila, R., Jahn, B. M., Lameyre, J. & Wang, Y. (1994). The Kuiqi peralkaline granite complex (SE China): Petrology and geochemistry. *Journal of Petrology* **35**, 983–1015.

McBirney, A. R. & Williams, H. (1969). Geology and Petrology of the Galapagos Islands. *Geological Society of America, Memoirs* **118**, 197 p.

McCurry, M., Hayden, K. P., Morse, L. H. & Mertzman, S. (2008). Genesis of post-hotspot, A-type rhyolite of the Eastern Snake River Plain volcanic field by extreme fractional crystallization of olivine tholeiite. *Bulletin of Volcanology* **79**, 361–383.

McDougall, I. (1962). Differentiation of the Tasmanian dolerites: Red Hill dolerite–granophyre association. *Geological Society of America Bulletin* **73**, 279–316.

Morse, S. A. (1980). Kiglapait mineralogy II. Fe–Ti oxide minerals and the activities of oxygen and silica. *Journal of Petrology* **21**, 685–719.

Nash, W. P., Carmichael, I. S. E. & Johnson, B. W. (1969). The mineralogy and petrology of Mount Suswa, Kenya. *Journal of Petrology* **10**, 409–439.

Oliveira, D. C., Dall'Agnol, R., Barros, C. E. M. & Oliveira, M. A. (2009). Geology, geochemistry and magmatic evolution of the Paleoproterozoic, anorogenic oxidized A-type Redenção granite of the Jamon Suite, eastern Amazonian Craton, Brazil. *Canadian Mineralogist* **47**, 1441–1468.

Orajaka, I. P. (1986). Geochemistry of Kaffo Valley albite–riebeckite-granite, Liruei granite ring-complex, Northern Nigeria. *Chemical Geology* **56**, 85–92.

Osborn, E. F. (1959). Role of oxygen pressure in the crystallization and differentiation of basaltic magma. *American Journal of Science* **257**, 609–647.

Patiño Douce, A. (1997). Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids. *Geology* **25**, 743–746.

Pitra, P. & De Waal, S. A. (2001). High-temperature, low-pressure metamorphism and development of prograde symplectites, Marble Hall Fragment, Bushveld Complex (South Africa). *Journal of Metamorphic Geology* **19**, 311–325.

Rämö, O. T. (1991). Petrogenesis of the Proterozoic rapakivi granites and related basic rocks of southeastern Fennoscandia: Nd and Pb isotopic and general geochemical constraints. *Geological Survey of Finland Bulletin* **355**, 161 p.

Rämö, O. T. & Haapala, I. (1995). One hundred years of rapakivi granite. *Mineralogy and Petrology* **52**, 129–185.

Riishuus, M. S., Peate, D. W., Tegner, C., Wilson, J. R. & Brooks, C.K. (2008). Petrogenesis of cogenetic silica-oversaturated and -undersaturated syenites by periodic recharge in a crustally contaminated magma chamber: the Kangerlussuaq Intrusion, East Greenland. *Journal of Petrology* **49**, 493–522.

Schmitt, A. K., Emmermann, R., Trumbull, R. B., Bühn, B. & Henjes-Kunst, F. (2000). Petrogenesis and ^{40}Ar/^{39}Ar geochronology of the Brandberg complex, Namibia: Evidence for a major mantle contribution in metaluminous and peralkaline granites. *Journal of Petrology* **41**, 1207–1239.

Scoates, J. S. & Lindsley, D. H. (2000). New insights from experiments on the origin of anorthosite. *EOS, Transactions of the American Geophysical Union* **81**, 1300.

Scoates, J. S., Frost, C. D., Mitchell, J. N., Lindsley, D. H. & Frost, B. R. (1996). Residual-liquid origin for a monzonite intrusion in a mid-Proterozoic anorthosite complex: The Sybille intrusion, Laramie anorthosite complex, Wyoming. *Geological Society of America Bulletin* **108**, 1357–1371.

Skjerlie, K. P. & Johnston, A. D. (1993). Fluid-absent melting behavior of an F-rich tonalitic gneiss at mid-crustal pressures: Implications for the generation of anorogenic granites. *Journal of Petrology* **34**, 785–815.

Smith, D. R., Noblett, J., Wobus, R. A., Unruh, D., Douglass, J., Beane, R., Davis, C., Goldman, S., Kay, G., Gustavson, B., Saltoun, B. & Stewart, J. (1999). Petrology and geochemistry of late-stage intrusions of the A-type, mid-Proterozoic Pikes Peak batholith (Central Colorado, USA): implications for petrogenetic models. *Precambrian Research* **98**, 271–305.

Stoeser, D. B. & Frost, C. D. (2006). Nd, Pb, Sr, and O isotopic characterization of the Saudi Arabian Shield terranes. *Chemical Geology* **226**, 163–188.

Stuckless, J. S., VanTrump, G., Jr, Christiansen, E. H., Bunker, C. M. & Bush, C. A. (1982). *Preliminary report on the geochemistry of postorogenic granites from the northeastern Arabian Shield, Kingdom of Saudi Arabia.* US Geological Survey Open-File Report USGS-OF-02-91.

Wager, L. R. & Brown, G. M. (1967). *Layered Igneous Rocks*. San Francisco, CA: W. H. Freeman, 588 p.

Whalen, J. B., Currie, K. L. & Chappell, B. W. (1987). A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* **95**, 407–419.

Whitaker, M. L., Nekvasil, H., Lindsley, D. H. & Difrancesco, N. J. (2007). The role of pressure in producing compositional diversity in intraplate basaltic magmas. *Journal of Petrology* **48**, 365–393.

Whitaker, M. L., Nekvasil, H., Lindsley, D. H. & McCurry, M. (2008). Can crystallization of olivine tholeiite give rise to potassic rhyolites—an experimental investigation. *Bulletin of Volcanology* **70**, 417–434.